

The scales of the Universe

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... the largest of them all



Notation

Greater than 1

$$10^1 = 10$$

$$10^2 = 100$$

$$10^3 = 1000$$

⋮

$$10^9 = 1000,000,000$$

(billion)

$$10^{12} = 1000,000,000,000$$

(trillion)

$$10^{100} = 1... (100 \text{ zeros})$$

(google)

Less than 1

$$10^{-1} = 1/10 = 0.1$$

$$10^{-2} = 0.01$$

$$10^{-3} = 0.001$$

⋮

$$10^{-9} = 0.000000001$$

(billionth)

$$10^{-12} = 0.0000000000001$$

(trillionth)

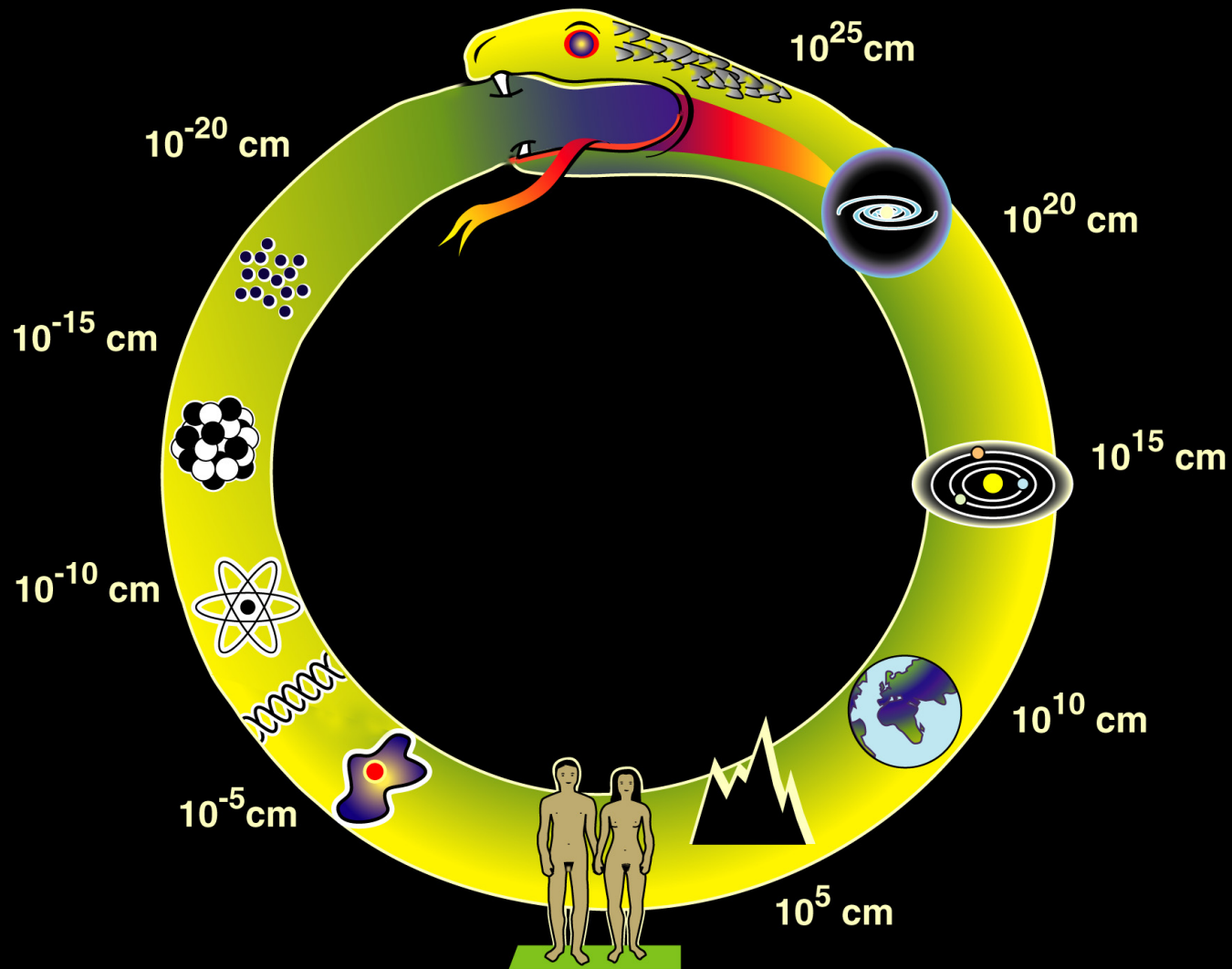
Notation

A **light year** (ly) is unit of **distance**: the distance travelled by light in 1 year

$$1 \text{ ly} \approx 10^{16} \text{ m} = 10^{18} \text{ cm}$$

about **100 times** the size of the **solar system**

The Ouroboros



The building blocks of the Universe

A hundred billion stars

100,000 ly





The Virgo cluster of galaxies

Virgo contains about 1000 galaxies and is
at a distance of 65 million light years
(650 Milky Way radii)

The background of the slide is a deep-field image from the Hubble Space Telescope, showing a vast field of galaxies. The galaxies are of various shapes and sizes, some appearing as bright, distinct objects while others are faint, distant specks. The colors range from deep blues and purples to bright oranges and yellows, representing different wavelengths of light captured by the telescope. The overall effect is a sense of immense scale and depth in the universe.

The Hubble ultra-deep field

Smaller than **tenth** of the diameter of the **moon**.
(Need **13 million** like this to **cover the sky**)

The “**visible**” universe contains about **100 billion galaxies** (each with about **100 billion stars**)

The **radius** of the visible universe is about **45 billion light years** (**1000 times the distance to Virgo**)

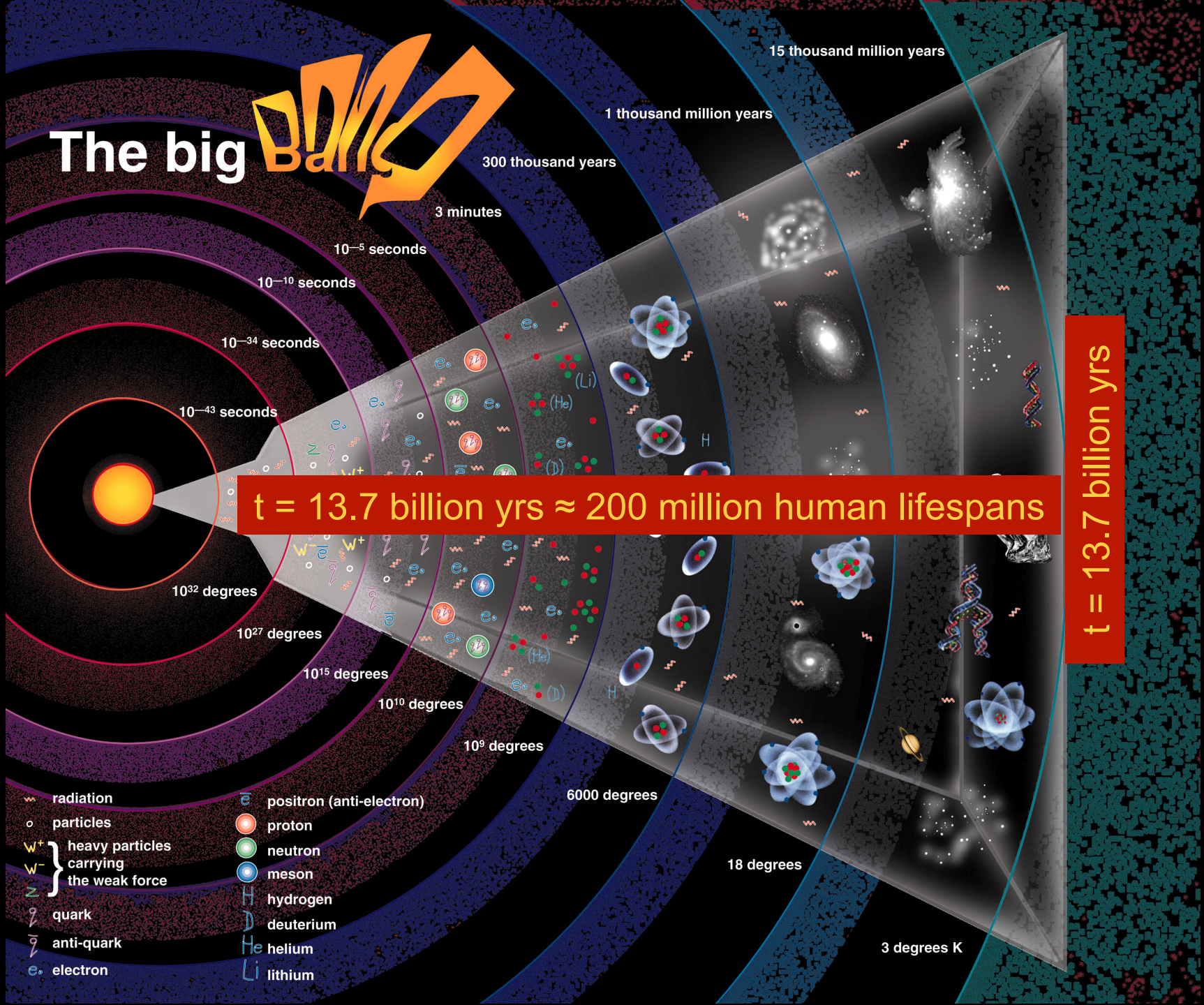
The background of the entire slide is a deep-field astronomical image from the Hubble Space Telescope, showing a vast field of galaxies. The galaxies are of various shapes and sizes, including spiral, elliptical, and irregular forms, scattered across a black cosmic background. Some galaxies are bright and clear, while others are faint and distant. The colors range from yellow and orange to blue and purple.

The Hubble ultra-deep field

The Universe is
BIG

and OLD

The big Bang



~ radiation

o particles

W⁺ heavy particles
W⁻ carrying
the weak force

q quark

q̄ anti-quark

e⁻ electron

e⁺ positron (anti-electron)

p proton

n neutron

m meson

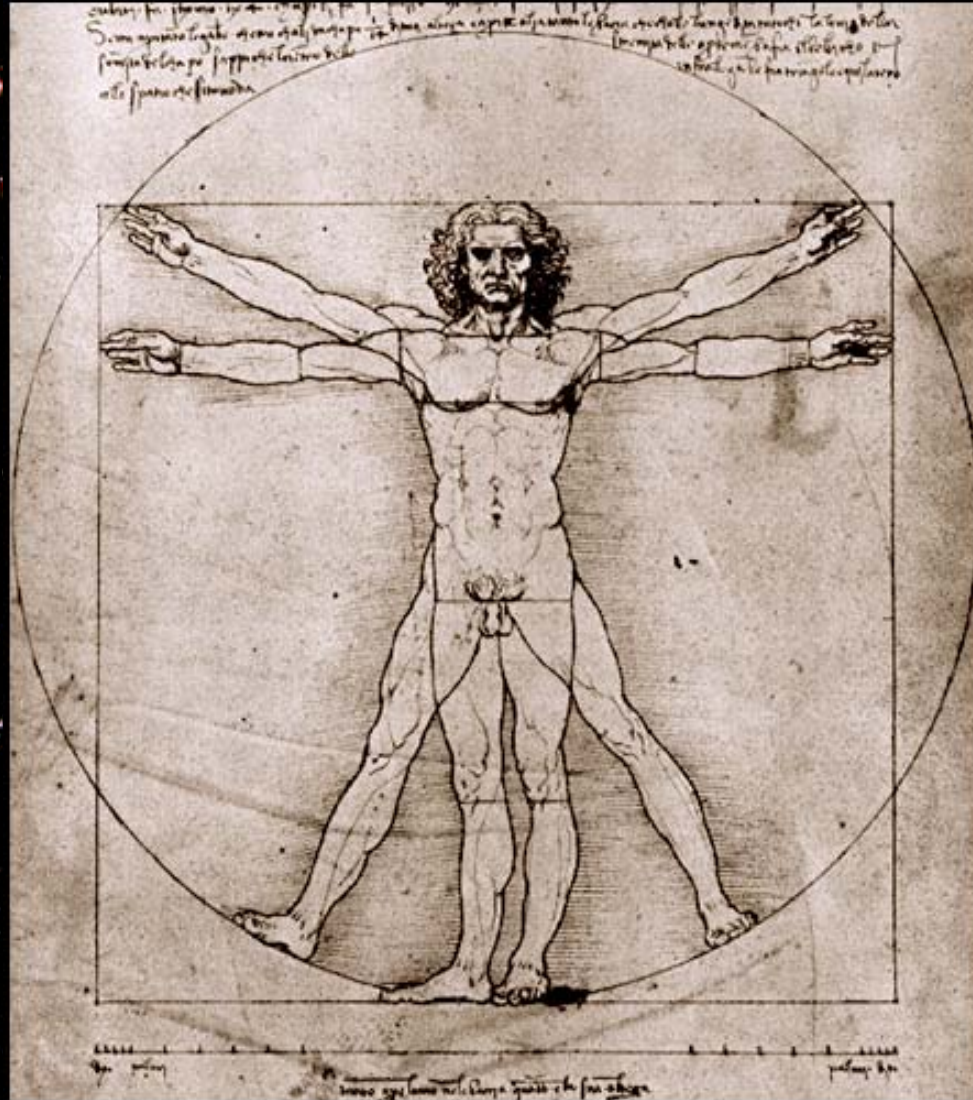
H hydrogen

D deuterium

He helium

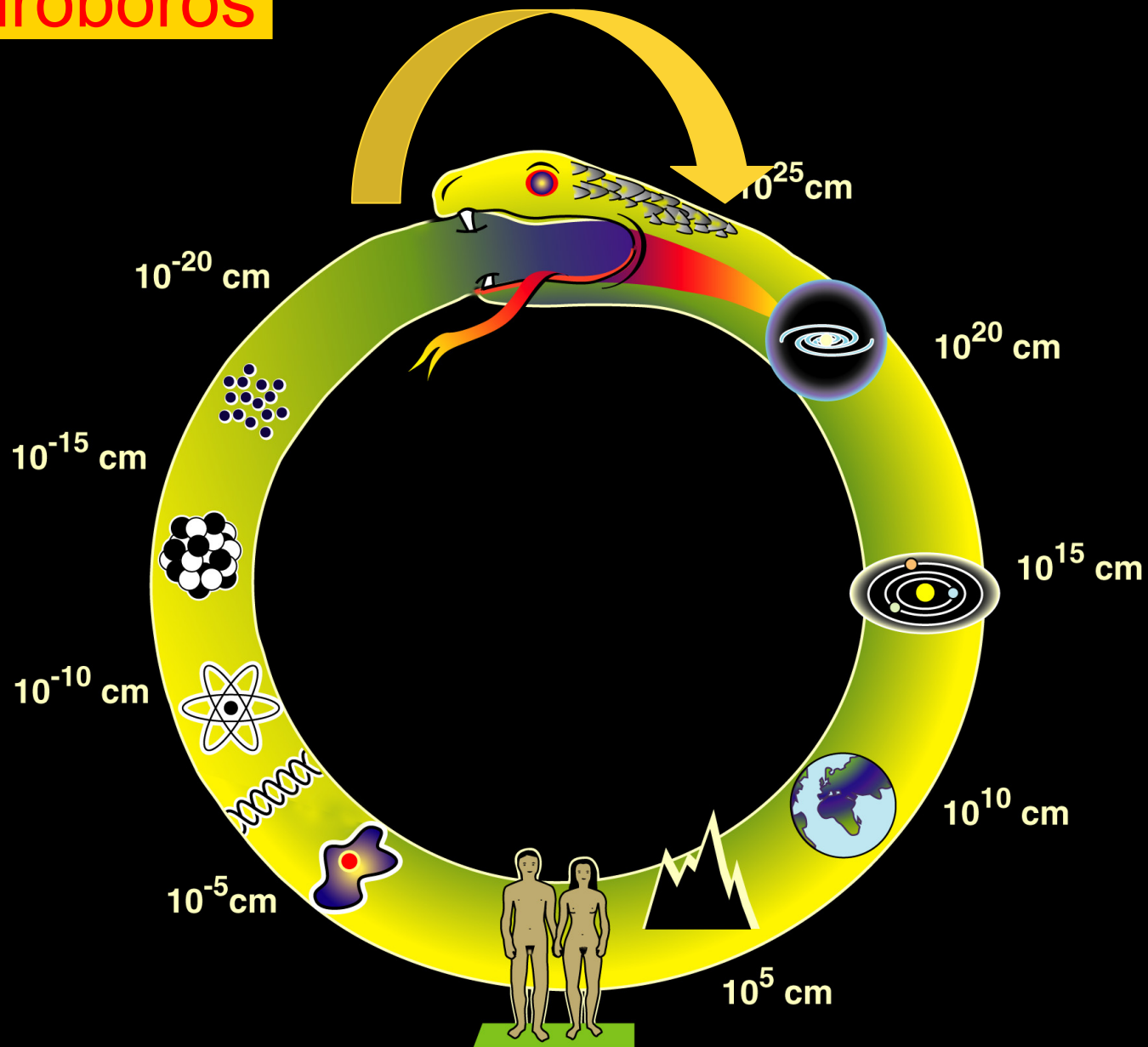
Li lithium

The Universe is BIG and old

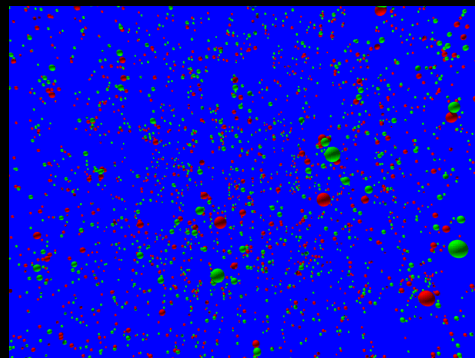


that makes things difficult to understand

The Ouroboros



The Ouroboros



10^{-15} cm

10^{-10} cm

10^{-5} cm

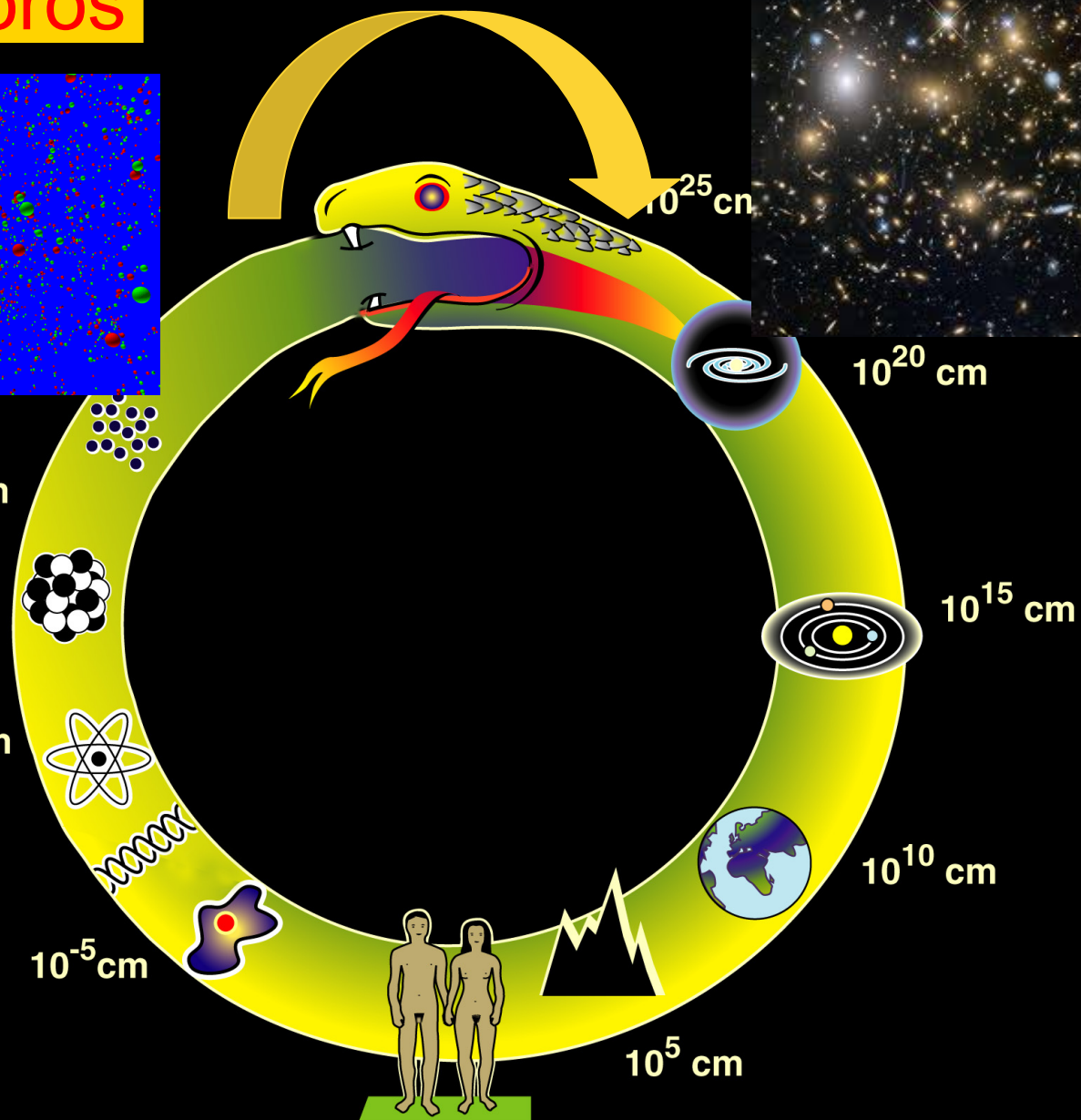
10^5 cm

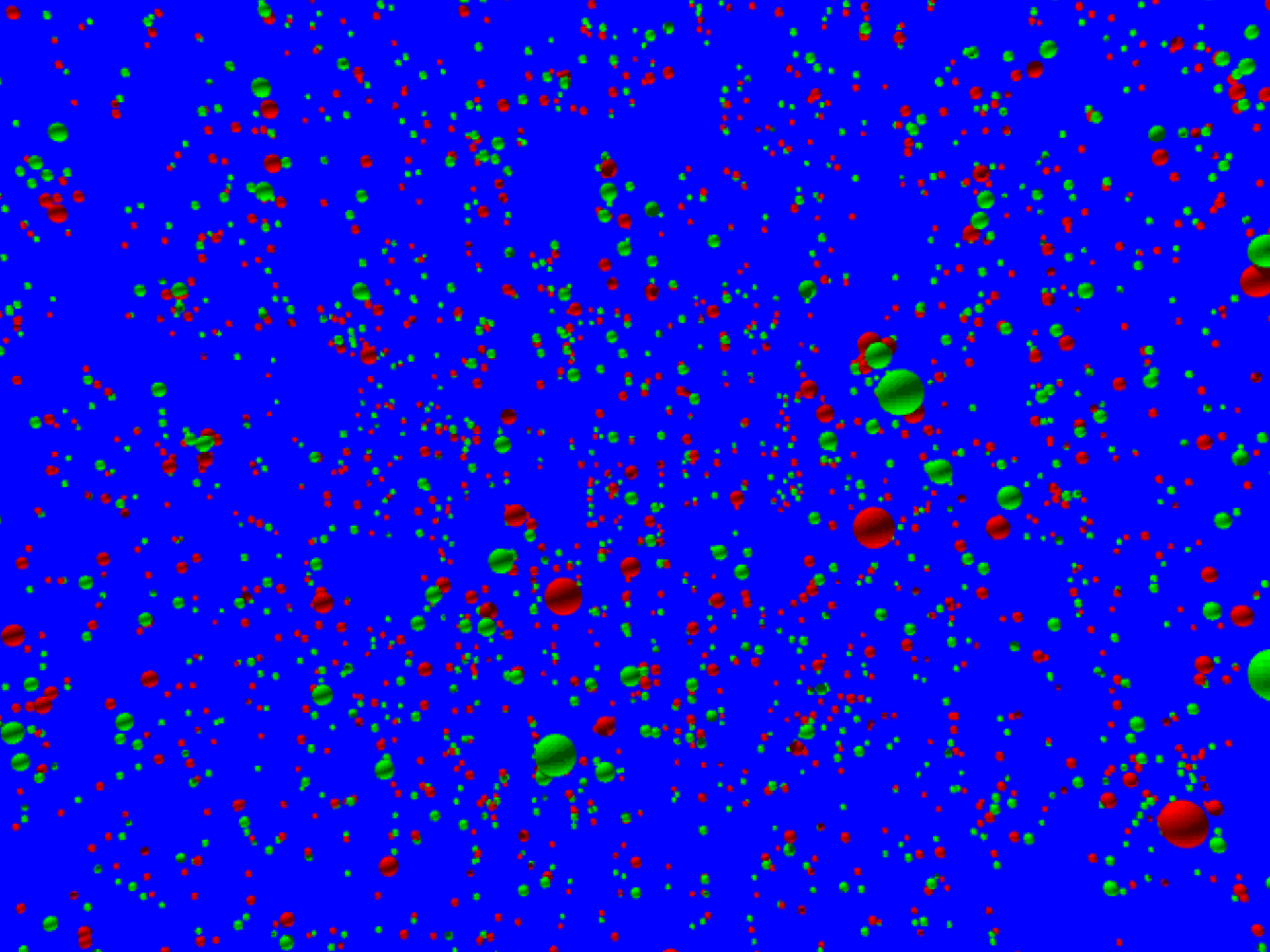
10^{10} cm

10^{15} cm

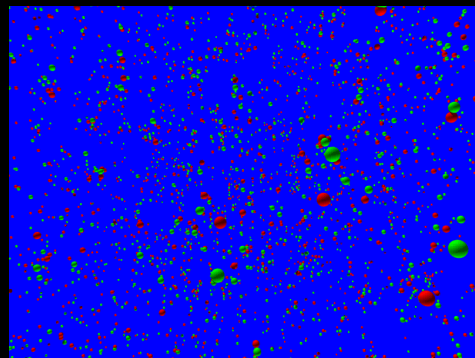
10^{20} cm

10^{25} cm





The Ouroboros



10^{-15} cm

10^{-10} cm

10^{-5} cm

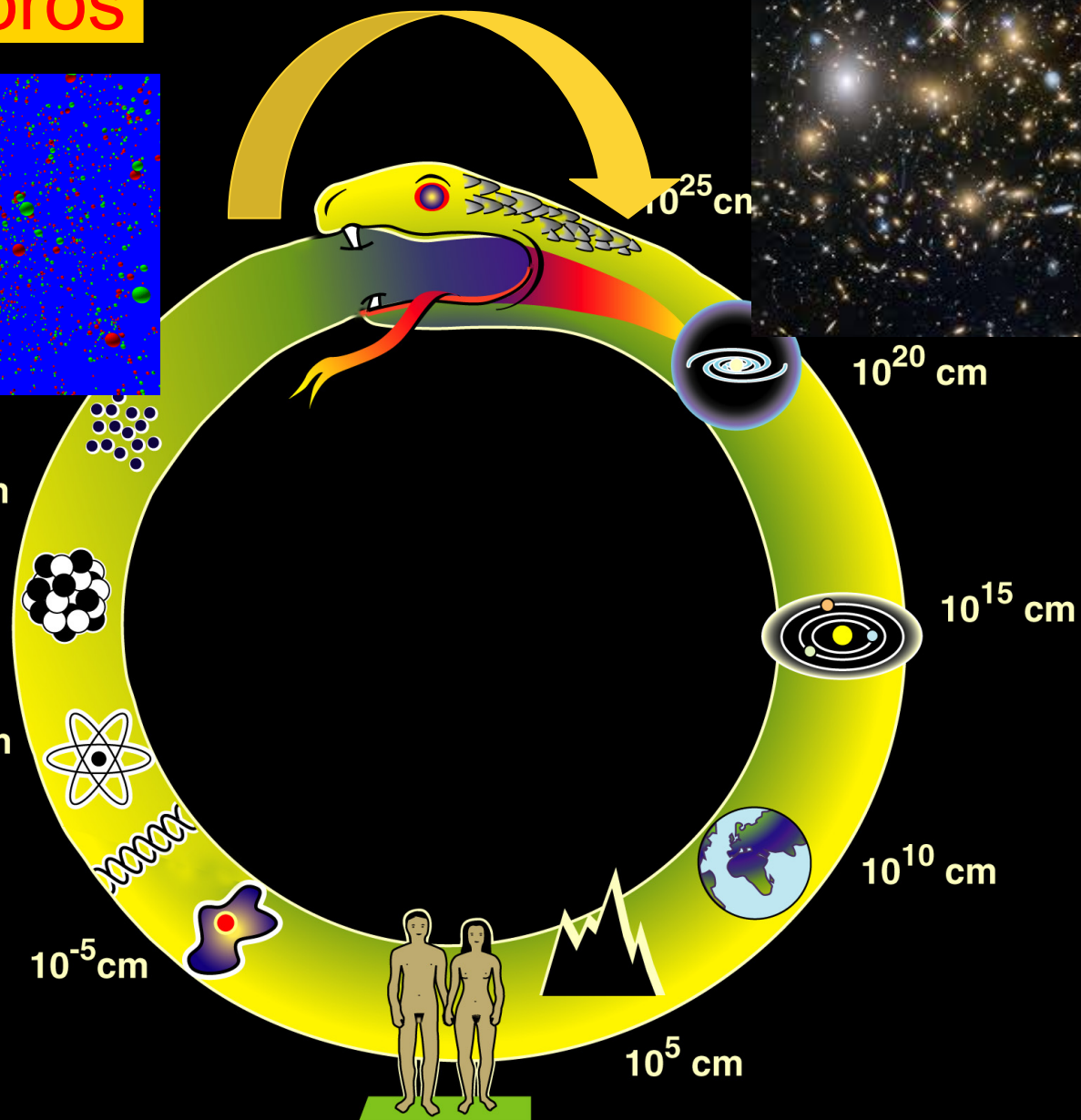
10^5 cm

10^{10} cm

10^{15} cm

10^{20} cm

10^{25} cm



Landmark moments in the early Universe

The heat from the Big Bang



By today, the radiation from the Big Bang has cooled to 2.7 degrees

The echo of the Big Bang

In 1964, Arno Penzias & Bob Wilson were carrying out experiments using a microwave antenna for satellite communications.

As they pointed the antenna towards the sky, their receiver registered a faint 'hiss' coming from all directions that would not go away.



The big Bang

15 thousand million years

The temperature of this radiation should show small irregularities

Production of dark matter
($t \sim 10^{-10}$ s)

300 thousand years

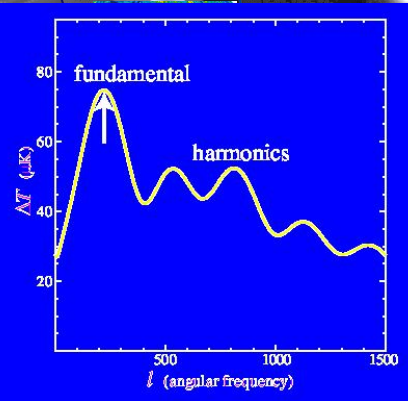
3 minutes

10^{-43} seconds

10^{32} degrees

10^{27} degrees

10^{15} degrees



$t = 13.7$ billion yrs

Cosmic inflation
(initial conditions)
($t \sim 10^{-35}$ s)

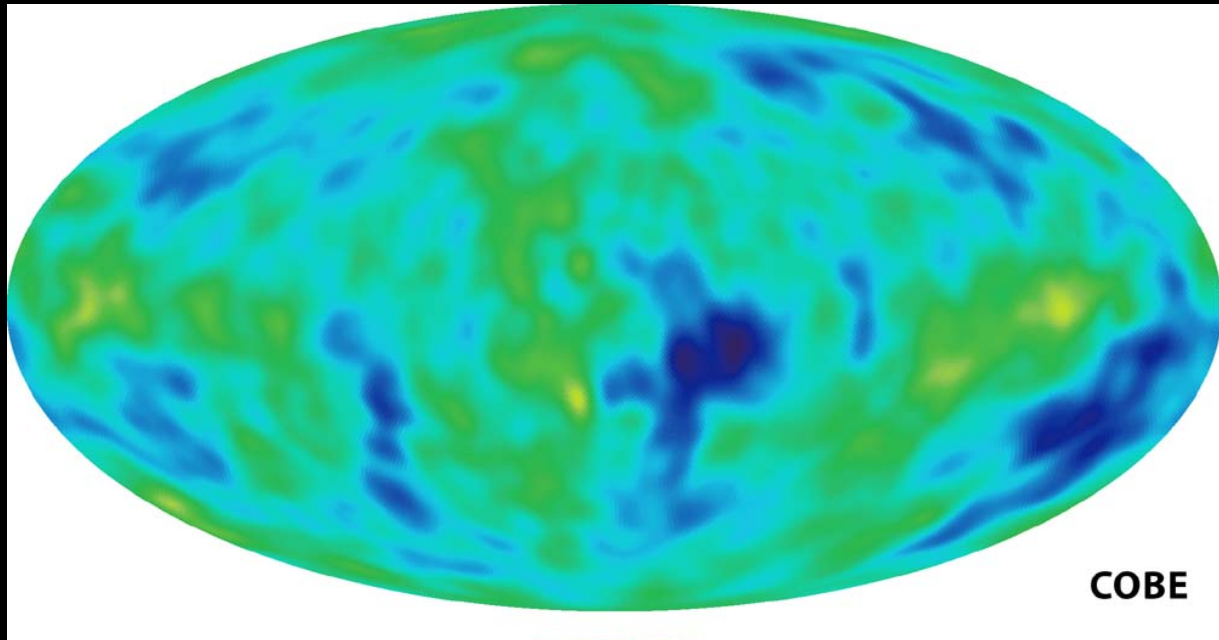
- | | |
|---|--------------------------------|
| γ radiation | e^+ positron (anti-electron) |
| \circ particles | p proton |
| W^+ heavy particles carrying the weak force | n neutron |
| W^- | m meson |
| Z | H hydrogen |
| q quark | D deuterium |
| \bar{q} anti-quark | He helium |
| e^- electron | Li lithium |

1 degrees

18 degrees

3 degrees K

1992



The cosmic microwave background radiation (CMB) provides a window to the universe at $t \sim 3 \times 10^5$ yrs

In 1992 COBE discovered temperature fluctuations ($\Delta T/T \sim 10^{-5}$) consistent with inflation predictions



No 1,722

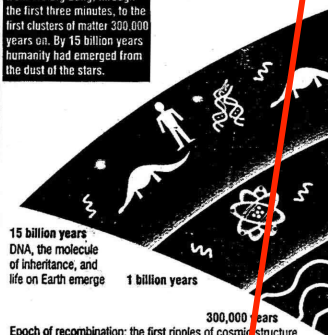
THE INDEPENDENT

A Nasa spacecraft has detected the stars after the Big Bang has

How

BACK TO CREATION

How the universe evolved from the Big Bang, through the first three minutes, to the first clusters of matter 300,000 years on. By 15 billion years humanity had emerged from the dust of the stars.



FOURTEEN thousand million years ago the universe hiccuped. Yesterday, American scientists announced that they have heard the echo.

A Nasa spacecraft has detected ripples at the edge of the Cosmos which are the fossilised imprint of the birth of the stars and galaxies around us today.

According to Michael Rowan-Robinson, a leading British cosmologist, "What we are seeing here is the moment when the structures we are part of — the stars and galaxies of the universe — first began to form."

The ripples were spotted by the Cosmic Background Explorer (Cobe) satellite and presented to excited astronomers at a meeting of the American Physical Society in Washington yesterday. "Oh wow... you can have no idea how exciting this is," Carlos Frenk, an astronomer at Durham University, said yesterday. "All the world's cosmologists are on the telephone to each other at the moment trying to work out what these numbers mean."

Cobe has provided the answer to a question that has baffled scientists for the past three decades: their attempts to understand the structure of the Cosmos. In the 1960s two American researchers found definitive evidence that the Big Bang had started the whole thing off about 15 billion years ago. But the Big Bang would have spread matter like thin gruel evenly throughout the universe. The problem was to work out how

the lumps (stars, planets and galaxies) got into the porridge.

"What we have found is evidence for the birth of the universe," said Dr George Smoot, an astrophysicist at the University of California, Berkeley, and the leader of the Cobe team.

Dr Smoot and colleagues at Berkeley joined researchers from several American research organisations to form the Cobe team. These included the

Goddard Space Flight Center, Nasa's Jet Propulsion Laboratory, the Massachusetts Institute of Technology and Princeton University. Joel Primack, a physicist at the University of California at Santa Cruz, said that if the research is confirmed, "it's one of the major discoveries of the century. In fact, the major discoveries of science."

Turner, a University of Chicago physicist, called the discovery "unbelievably important... The significance of this cannot be overstated. They have found the Holy Grail of cosmology. It is indeed correct, this could have to be considered for a Nobel Prize."

Since the ripples were created almost 15 billion years ago, their radiation has been travelling toward Earth at the speed of light. By detecting the radiation, Cobe is "a wonderful time machine"

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3 minutes

1 second

Stable subnuclear particles, neutrons and protons, are formed

10⁻¹⁰ second

10⁻³
The quarks bare parti

able to view the young universe, Dr Smoot said.

A remnant glow from the Big Bang is still around today, in the form of microwave radiation that has bathed the universe for the billions of years since the explosion. Galaxies must have formed by growing gravitational forces bringing matter together. To produce a "lumpy" universe, radiation from the Big Bang should itself show signs of being lumpy.

Cobe, which has been orbiting 500 miles above the Earth since the end of 1989, has instruments on board that are sensitive to this extremely old radiation. The ripples Cobe has found are the first hard evidence of the long-sought lumpiness in the radiation.

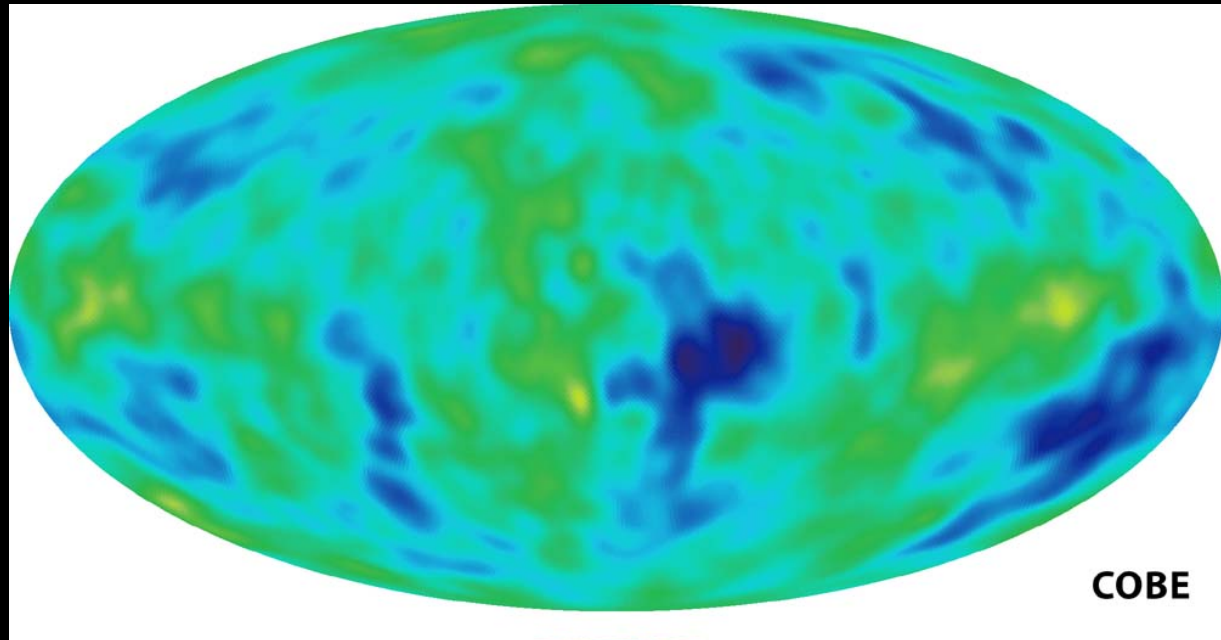
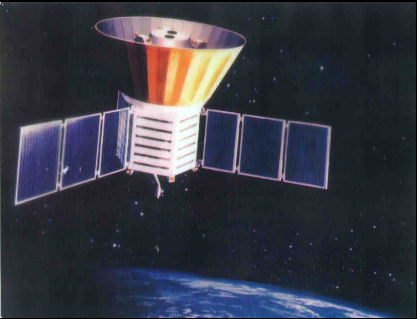
Cobe detected almost imperceptible variations in the tem-

ceptible variations in the temperature... surrounded by slightly less dense... time when the foggy fireball of radiation... and light from these galaxies, re-emitted... predictions about what the size of the original fog lifted.

Flammarion 1888: tete des etoiles

The CMB

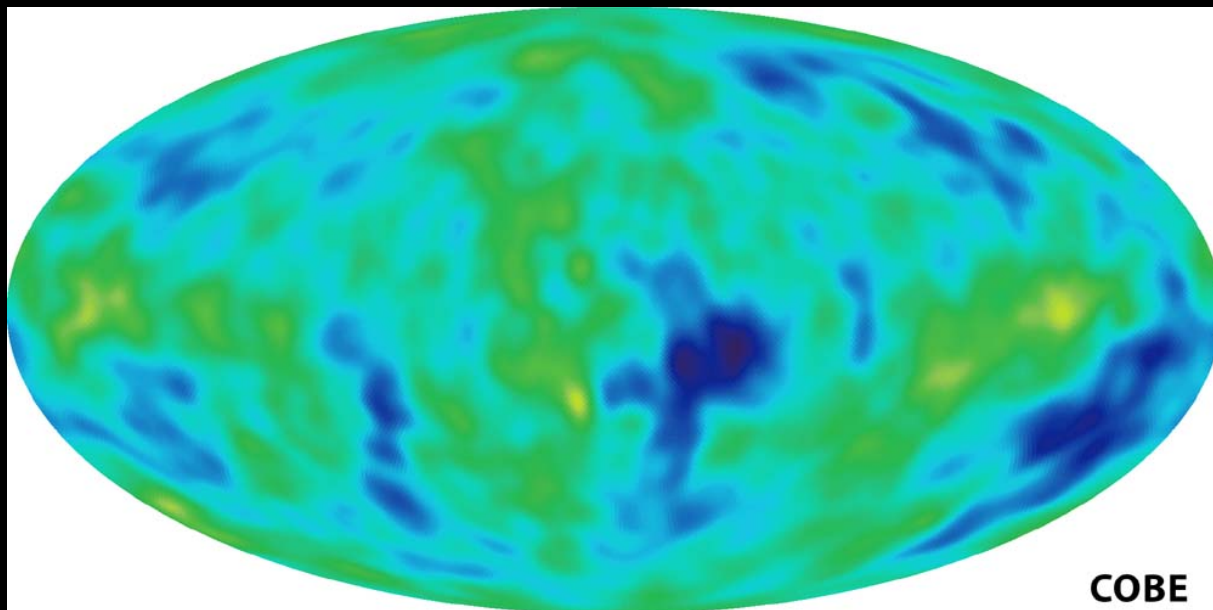
1992





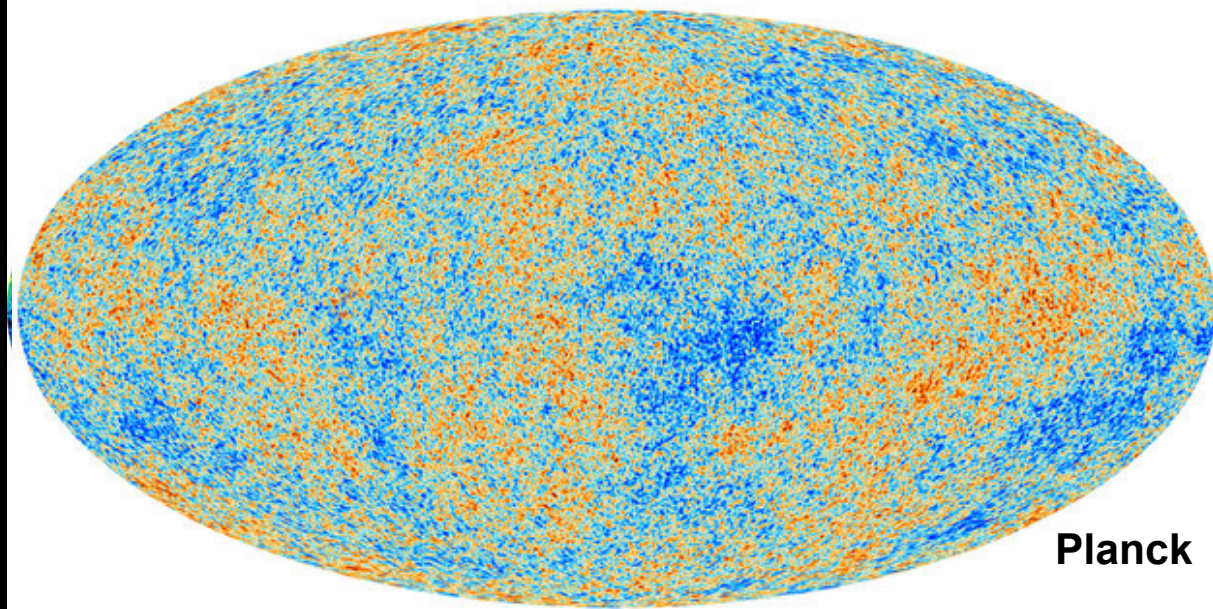
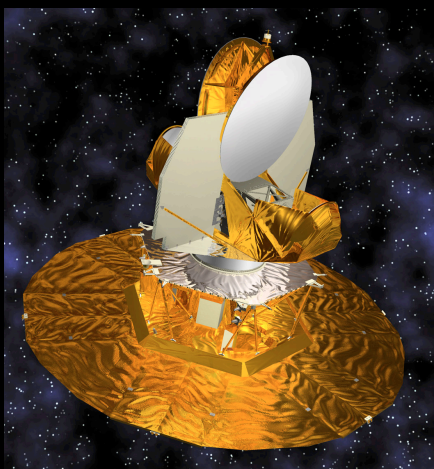
The CMB

1992



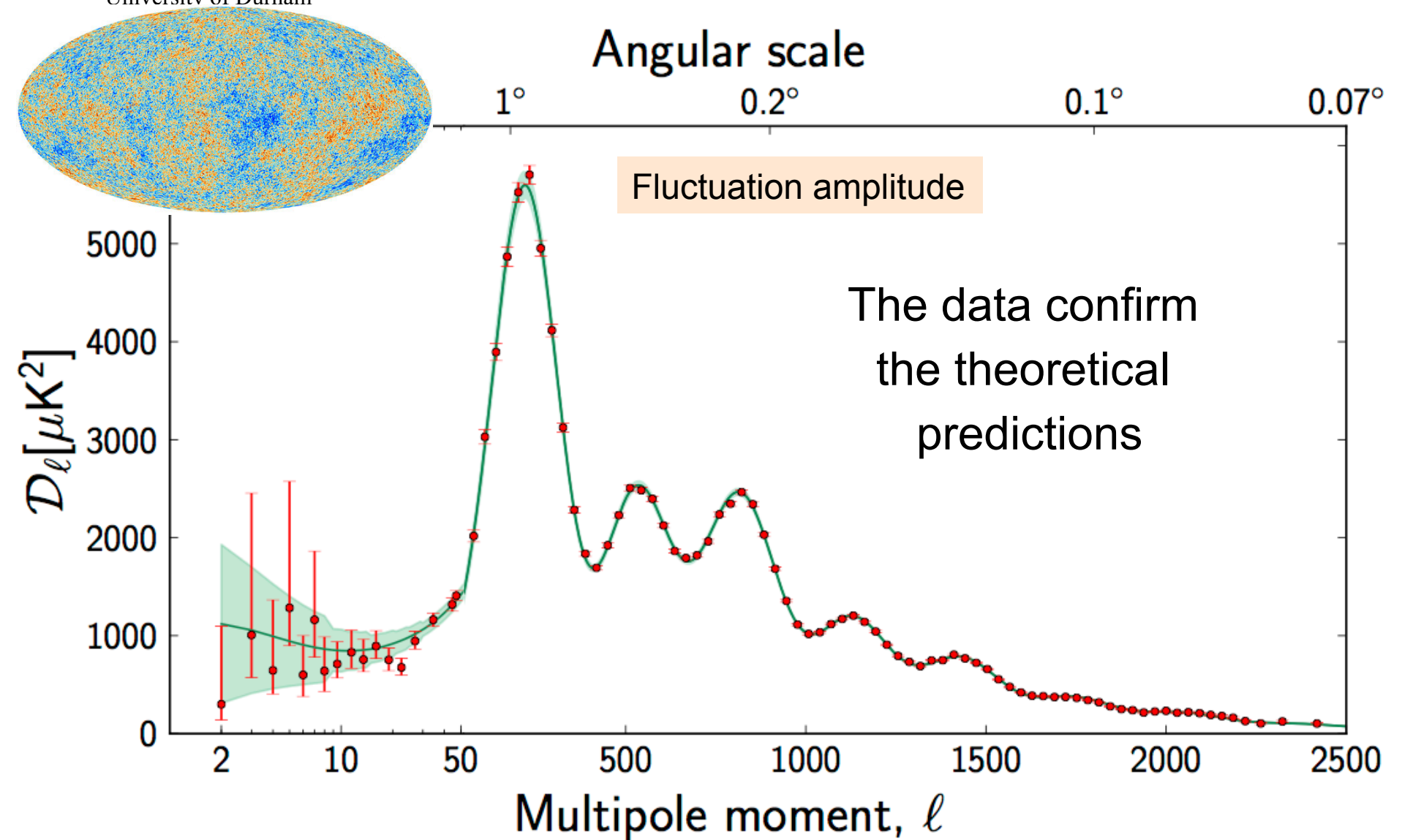
COBE

2012



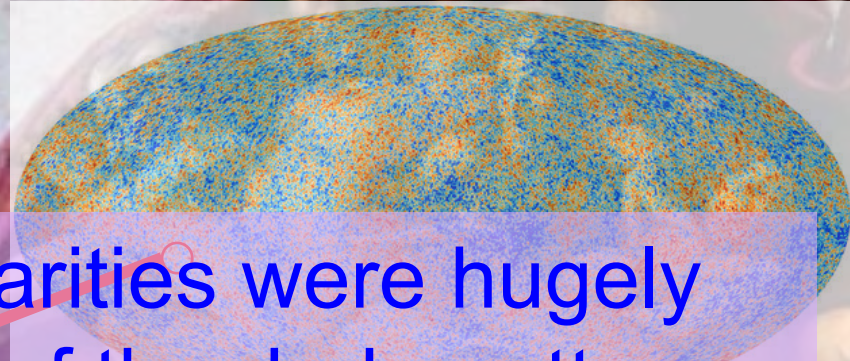
Planck

Planck: CMB temperature anisotropies

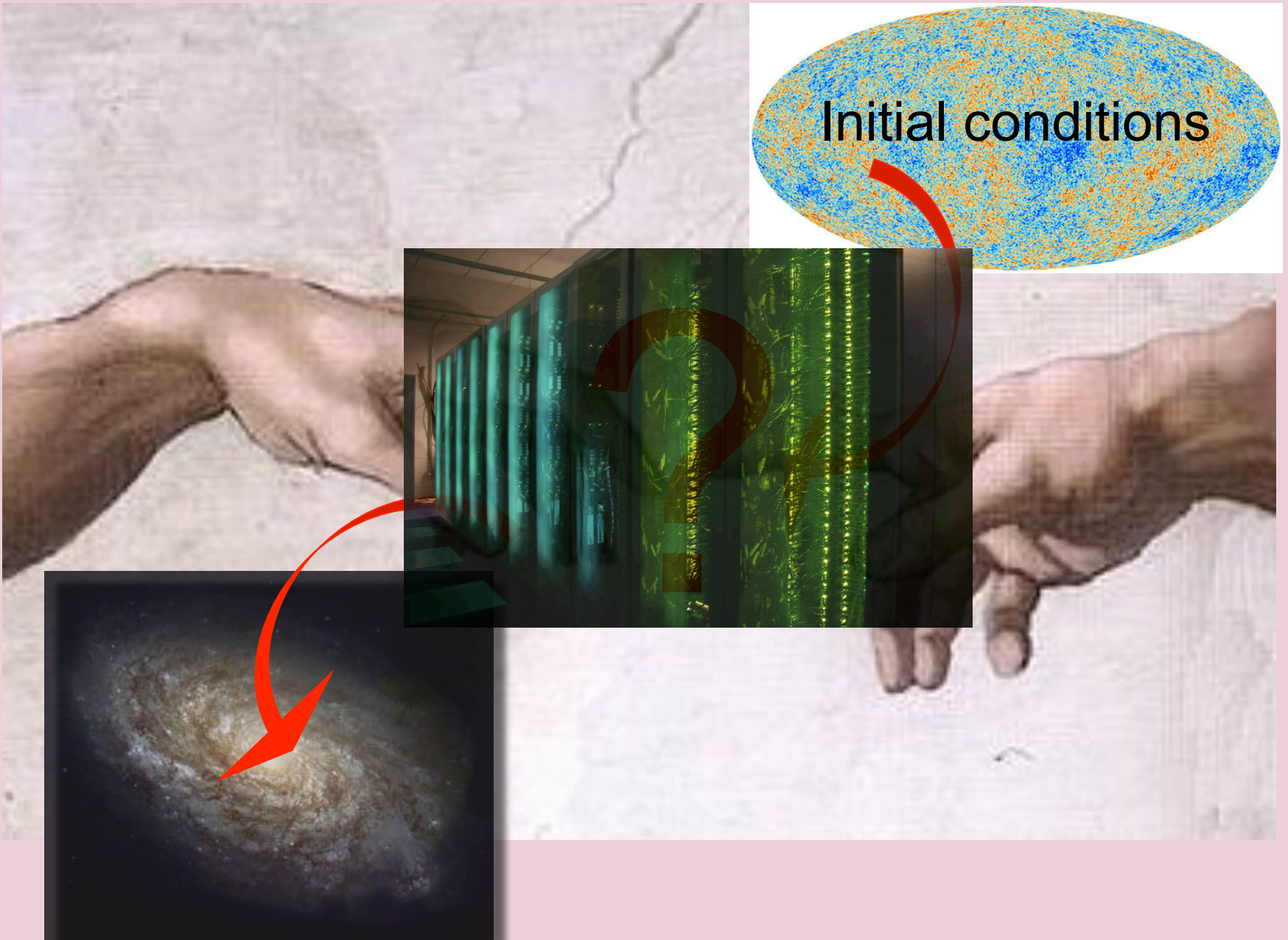


How did galaxies form?

The tiny quantum irregularities were hugely amplified by the gravity of the dark matter



The formation of galaxies



How to make a virtual universe

Initial conditions + assumption about content of Universe

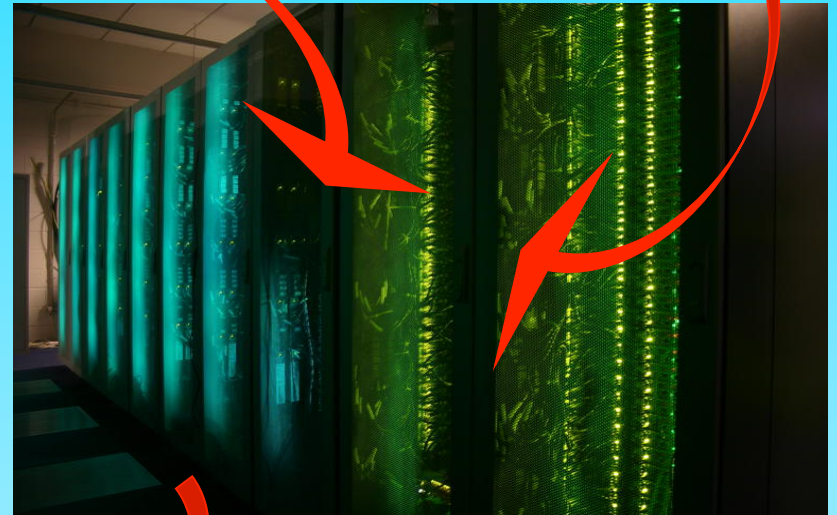
Equations of physics:

General Relativity

Mechanics

Radiative hydrodynamics

Atomic physics, etc

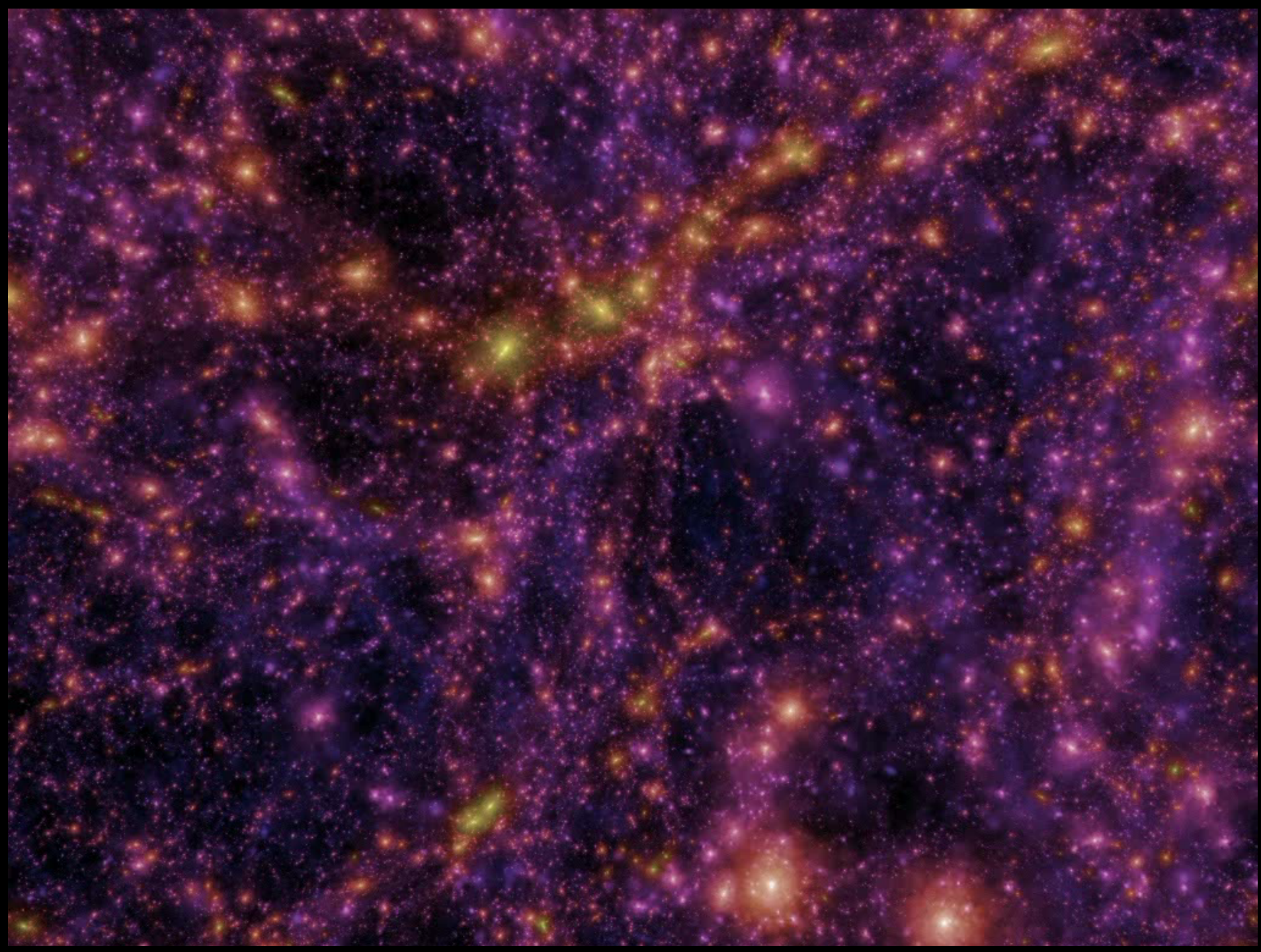


$z = 48.4$

$T = 0.05 \text{ Gyr}$

500 kpc

The image shows a dark, textured field of purple and black, representing a simulated galaxy at a very early stage. The texture is grainy and noisy, with some brighter, more defined regions that suggest the formation of structures. A scale bar at the bottom center indicates a length of 500 kpc.



The EAGLE simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

A project of the Virgo consortium

$z = 19.9$

$L = 25.0 \text{ cMpc}$

Visible components:
CDM

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations

E0

E7

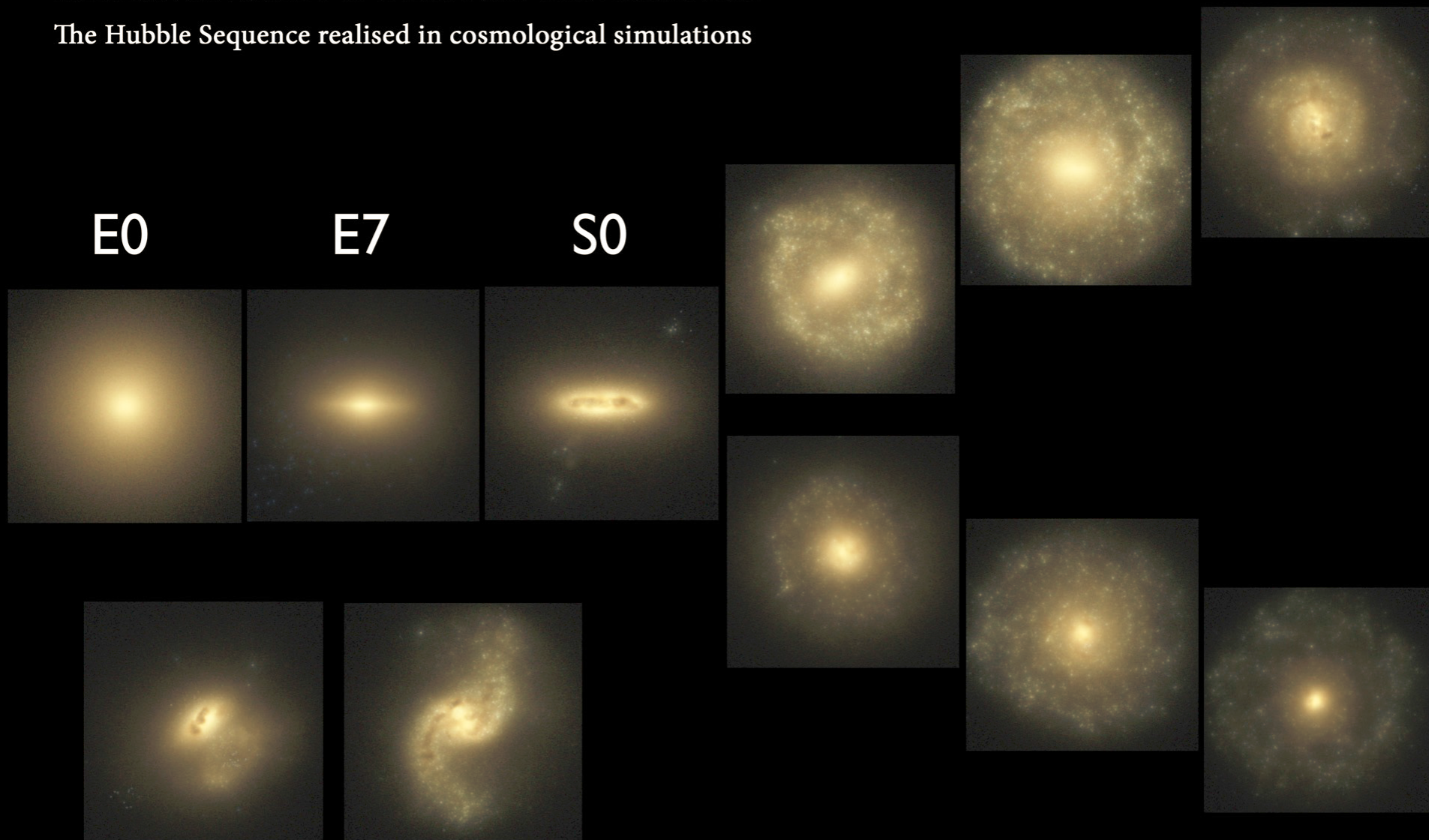
S0

SB

Irr

S

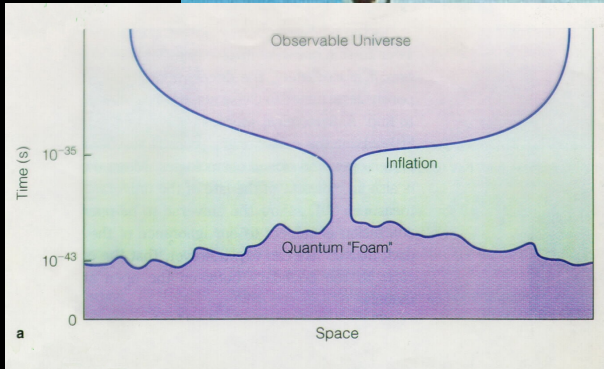
Trayford et al '15





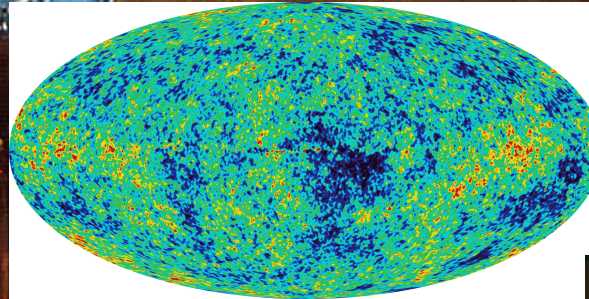
The origin of cosmic structure

Inflation ($t \sim 10^{-35}$ s)



Small (quantum) ripples

CMB ($t \sim 3 \times 10^5$ yrs)



Galaxies
($t \sim 13 \times 10^9$ yrs)

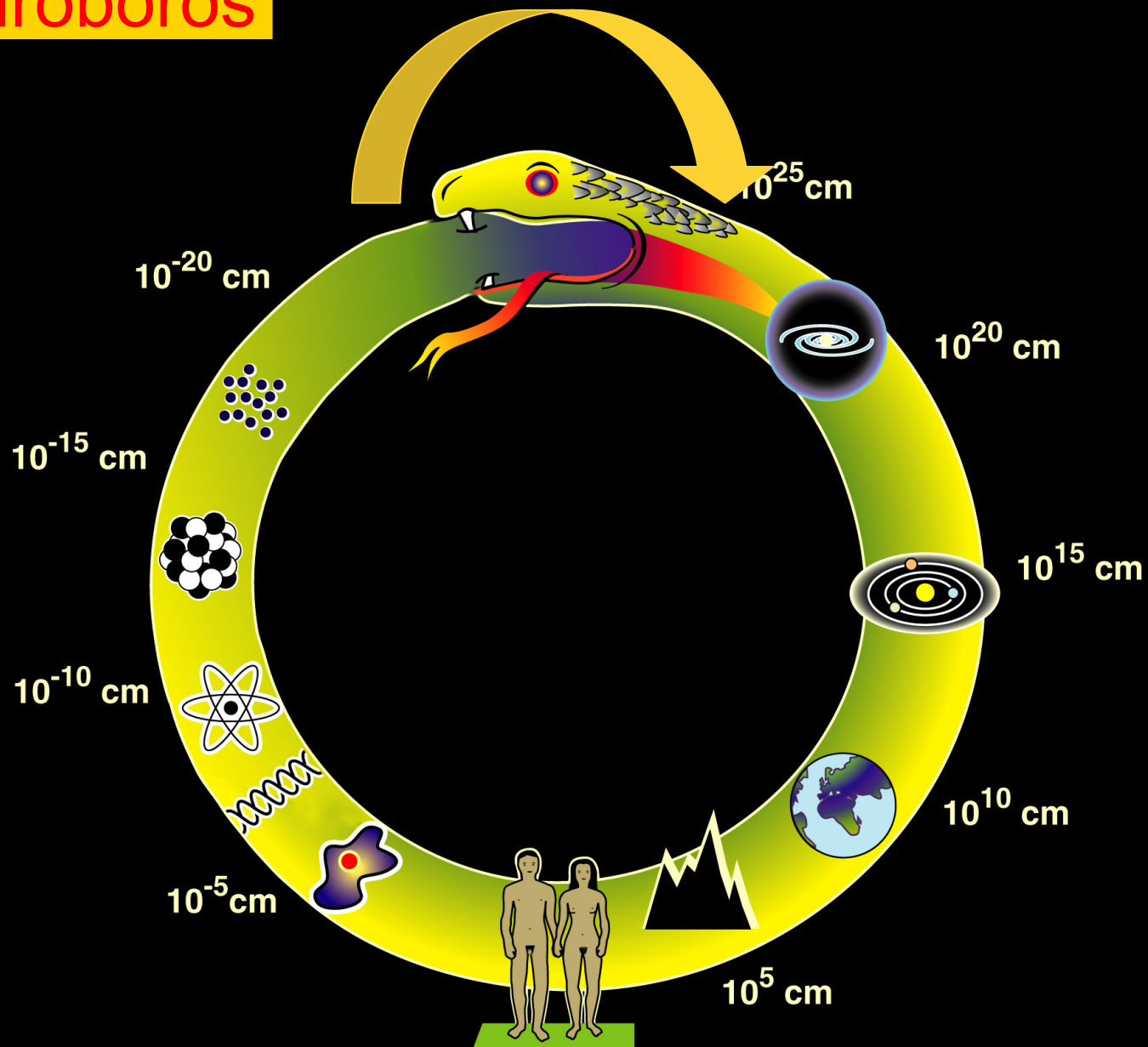
Cold dark matter

Ripples seen as hot & cold spots
in cosmic radiation

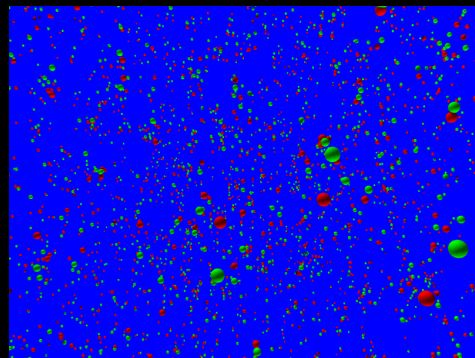
Recent **measurements** of CMB
temperature fluctuations and of the galaxy
distribution **confirm this paradigm.**



The Ouroboros



The Ouroboros



10^{-15} cm

10^{-10} cm

10^{-5} cm

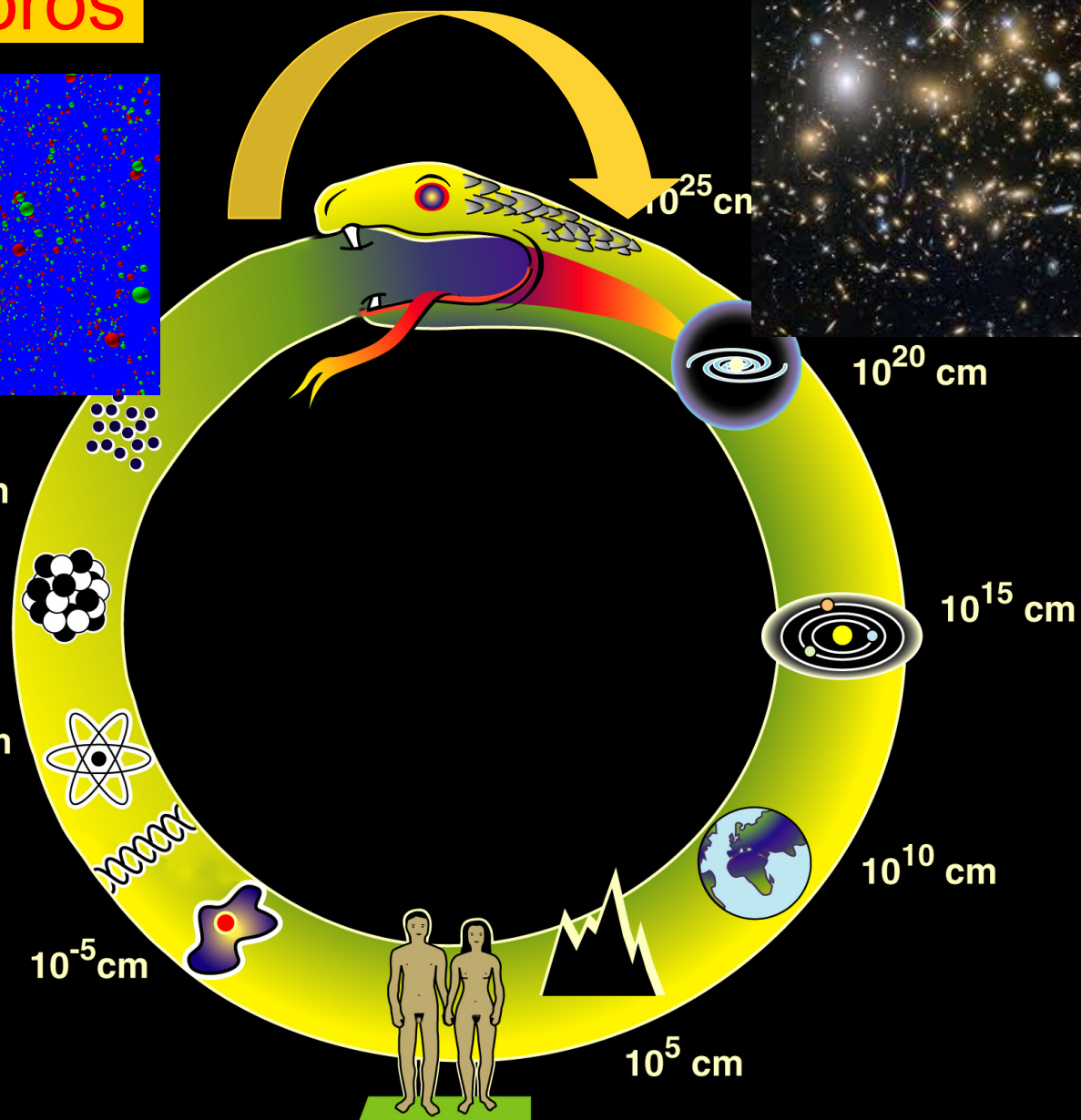
10^5 cm

10^{10} cm

10^{15} cm

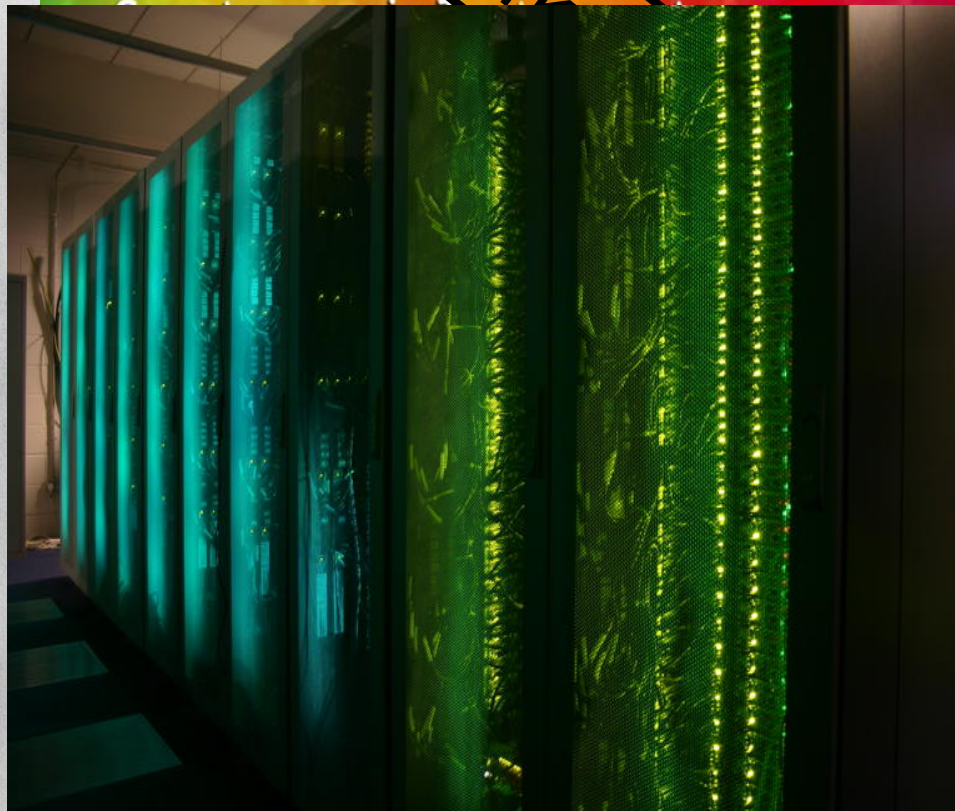
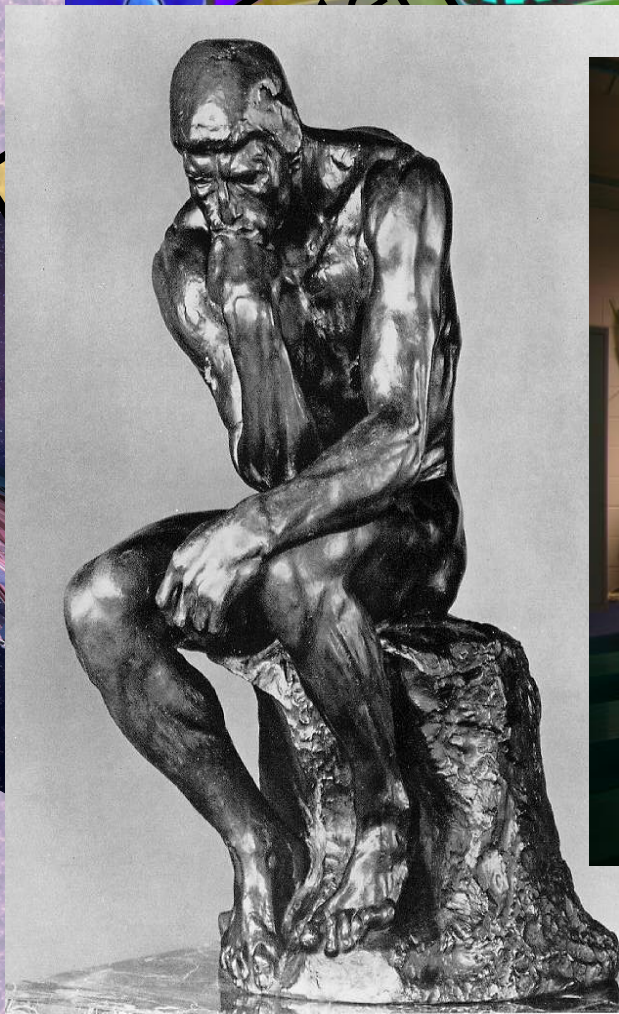
10^{20} cm

10^{25} cm



The future

Theory, computing and modelling



Telescope

Large Synoptic Survey

There seems to be a deep connection between the
small and the large, the microscopic and the universe

